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ABSTRACT

The successful completion of the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), followed by a campaign to achieve ignition, creates the proper conditions to begin exploring what development work remains to construct a power plant based on Inertial Confinement Fusion (ICF) technology. Fundamentally, two distinct NIF laser properties must be overcome. The repetition rate must increase from a shot every four hours to several shots per second. Additionally, the efficiency of converting electricity to laser light must increase by 20× to roughly 10 percent. Solid state diode pumped lasers, commercially available for table top applications, have adequate repetition rates and power conversion efficiencies, however, they operate at a tiny fraction of the required energy for an ICF power plant so would need to be scaled in energy and aperture. This paper describes the optics and coatings that would be needed to support this type of laser architecture.

Keywords: Laser glass, fused silica, KDP, DKDP, laser resistance, mirrors, polarizers, optical thin films

1. INTRODUCTION

Fusion laser systems have grown in power and size with advances in technology. The latest laser system named the National Ignition Facility shown in figure 1 is a 1.8 MJ laser with a wavelength of 351 nm and flexible pulse shaping capabilities.[1-4] One of the main purposes of this facility is the demonstration of Ignition in a controlled laboratory setting. The ignition process involves fusing a tritium and deuterium atom together to yield a helium atom and an energetic neutron. The fusion process overcomes a disadvantage of the fission process where only a small amount of the nuclear fuel is depleted due to a lack of available neutrons thus creating a radioactive waste stream. A Laser Inertial Fusion Energy (LIFE) based system is being proposed as an energy solution that is carbon free and burns spent nuclear fuel.[5] In a LIFE engine, a neutron-rich inertial fusion point source drives an energy-rich fission blanket to generate energy, make its own fuel, and incinerate waste.

Figure 1 The National Ignition Facility, completed in 2009, was constructed to demonstrate laser fusion in the quest for an energy alternative to fossil fuels.

Today's fusion lasers are low repetition rate machines with poor electrical to laser light conversion efficiencies. Therefore, the next generation fusion laser will be based on diode-pumped solid state laser technology and require thermal control to maintain beam quality. This laser architecture has been demonstrated in sub-aperture at LLNL on the Mercury laser.[6] A 20-year timeline has been proposed for developing and constructing a LIFE engine for commercialization of power generation.[5] This same proposal envisions 50% of the US expected electric consumption to be met with LIFE engines by 2100. In order to construct the National Ignition Facility, a multi-year research, development, and facilitization program was enacted to increase large optics fabrication by up to an order of magnitude with realization of cost reductions up to five times.[7] A comparable increase in large optics fabrication could be envisioned to build commercial LIFE engines.

2. LIFE OPTICS

Preliminary conceptual laser system designs have been proposed for a LIFE engine.[8] The basic laser architecture significantly leverages experiences learned from the National Ignition Facility and the Mercury laser. Because of the higher repetition rate and associated thermal loading, the optics will need to be engineered with lower absorption or better thermal characteristics.

Amplifier slabs in the NIF laser are continuously poured Nd doped phosphate laser glass.[9-10] Amplifier slabs in a LIFE laser will have to become significantly thinner or a different material composition. Transparent ceramics[11] offer higher thermal conductivity comparable to single crystals without the doping limitations at about 25% of the current aperture planned for a LIFE laser. Yb:S-FAP [Yb^{3+}:$Sr_5(PO_4)_3F$] crystals[12] are used for amplification on the Mercury laser. This crystal is currently grown by the Czochralski method and would need to be significantly scaled-up by the Schott Lithotec Bridgman technique before being a viable material for a LIFE laser.

A Pockels cell is an electro-optic switch used for parasitic isolation and multi-passing for more efficient extraction of the stored energy in the amplifier slabs. Frequency conversion crystals are used to convert the laser to a shorter wavelength. In the NIF laser, single potassium dihydrogen phosphate (KDP) crystals are used in the Pockels cells and second harmonic generators.[13-14] Deuterated potassium dihydrogen phosphate (DKDP) crystals are used for third harmonic generators. LIFE pockels cells and frequency conversion crystals will all be manufactured from DKDP because of the lower absorption. Significantly higher deuteration levels (>98% versus 70% for NIF) will also be needed to minimize absorption. Despite the precautions taken to reduce absorption, further heat extraction will be required. In addition to forced gas cooling, optical heat sinks such as sapphire may be used. Frequency conversion on the Mercury laser is achieved with an alternative crystalline material, yttrium calcium oxyborate (YCOB) as a second harmonic generator.[15] Scale-up in aperture of this material would be necessary for a LIFE laser.

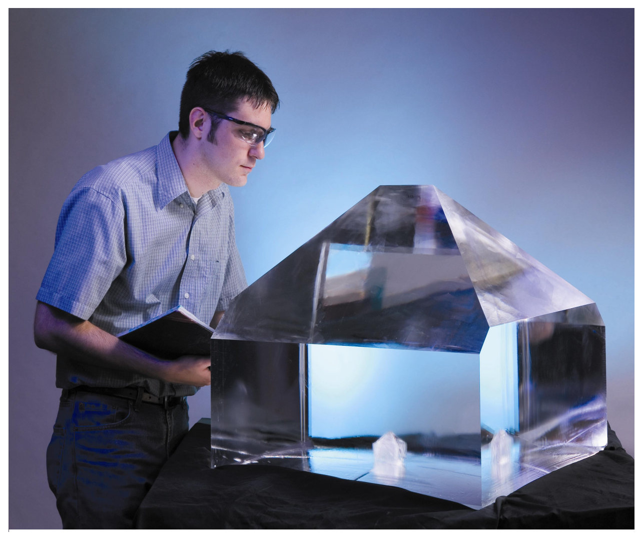

Figure 2 KDP crystal grown to manufacture second harmonic generator optics for NIF.

Two approaches in fusion lasers are used for beam transport into the target chamber. On the NIF laser the frequency conversion occurs just before the light is focused into the target chamber. Transport mirrors have a higher laser resistance at 1053 nm than at 351 nm. To maintain polarization purity into the conversion crystals, all of the transport mirrors need to be in-plane reflections. Alternatively, frequency conversion is done before the transport mirrors on some fusion laser systems. An advantage of this approach is that unconverted light is not transported into the target chamber and focused near the target. Also the number of transport mirrors is minimized because out-of-plane reflections are possible. Interest in 527 nm fusion laser drivers,[16-17] which have higher conversion efficiencies and hence higher drive energies, are a potential architecture for a LIFE engine. Advances in thin film laser resistance at visible wavelengths could enable a 527 nm transport LIFE engine.

An additional development area is with short pulse (picoseconds) Petwatt lasers that can be used to reduce the necessary target compression and hence overall laser drive energy. Long pulse amplifiers could be used with stretched pulses and high laser resistant multilayer diffraction gratings to compress the pulses just before entering the target chamber.[18-19] The production of high fluence multi-layer gratings remains a very active area of research.[20-21]

3. MANUFACTURING TECHNOLOGIES

Significant optical materials development will be required for the next generation fusion laser. The laser glass composition used on NIF was not optimized for high repetition rates. If current glass compositions were used, then slabs would have to be thinned from 40 mm to 8 mm. Thin slabs have two distinct disadvantages from a fabrication perspective. First the number of surfaces increases by five times. Secondly, it is more challenging to achieve the transmitted wavefront on a thinner slab. The better the surface quality, the thicker the slab can be because of the higher thermal loading it can tolerate. The semiconductor industry utilizes double-sided polishing, robotics, and ultra-clean polishing processes to achieve extremely high surface quality wafers. Double-sided pad polishing achieves a much higher finishing rate than the conventional pitch polishing process currently used for NIF amplifier slabs, however, this process yields a transmitted wavefront at least an order of magnitude worse than the current specification. Higher determinism is needed to achieve a transmitted wavefront of better than 0.3 waves p-v. Alternatively, highly deterministic small-tool figuring technologies such as computer-controlled polishing or Magnetorheological Finishing (MRF) could be used to bring slabs into full transmitted wavefront compliance.

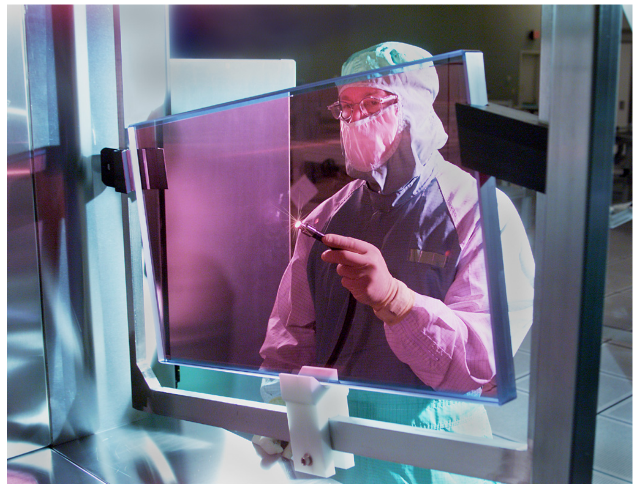

Figure 3 Nd-doped phosphate laser glass is the gain medium for NIF.

MRF has also been used for fusion optics for a number of specific applications and will continue to play a significant role in optics fabrication for next generation fusion optics. The imprinting of phase structures into an optic enable precise control of beam shaping.[22] High laser resistant UV fused silica surfaces have been demonstrated.[23] The MRF polishing process occurs at high shear forces which can lead to minimal subsurface damage instead of high compressive loads typical of pitch polishing. Current research of KDP finishing has shown significant promise for minimizing diamond turning marks thus lowering surface roughness. MRF has also shown promise for increasing the surface laser resistance of KDP crystals.[24] MRF has been successfully applied to extremely hard materials such as sapphire to correct for crystal growth-induced transmitted wavefront errors even at sub-millimeter spatial frequencies. Today MRF machines are available for fabricating meter-scale optics so is a tool ideally suited to advanced optics fabrication for high-power large-aperture laser applications.

Large-aperture high-fluence optical multilayer mirror and polarizer coatings for fusion lasers are traditionally deposited by electron beam deposition due to the ease of scaling to large apertures.[25] E-beam films are porous so suffer from spectral and wavefront changes over a humidity range.[26-27] A limitation of e-beam deposition is a high concentration of source defects that become inclusions with the multilayer forming nodular defects. Although there are processes today such as ion beam sputtering that have fewer defects (greater than an order of magnitude), the defects within e-beam films are loosely bound so if gently ejected through laser conditioning, high laser resistant pits remain. Dense films from more energetic processes do not have spectral or stress changes with humidity and tend to have a lower concentration of defects. Unfortunately the defects

Figure 4 NIF polarizers are combined with a KDP crystal in a Pockels cell, an electro-optical switch.

tend to be more tightly bound so catastrophically eject when irradiated. These catastrophic ejections cause damage sites with low-fluence growth thresholds.

Clearly a post processing (mitigation) technique that could arrest the growth of catastrophic defect ejections would make densified films a viable option for fusion lasers to take full advantage of the environment stability and improved film quality. Mitigation processes for UV-induced damage in fused silica and DKDP has been an active area of research for some time.[28-30] The laser-based techniques utilized for fused silica mitigation have not lent themselves well to multilayered materials with different absorbance values and thermal expansion coefficients. The mitigation shape can also have a fairly significant effect on the standing-wave electric fields within the multilayer structure.[31] Femtosecond laser machining is showing some promise because of the minimal thermal loading during the machining operations, the ability to precisely control the shape of the machined pit, and promising laser resistance.[32] Clearly significant research is needed before bringing a mitigation process into production, but initial results are promising.

527 nm transport mirror coatings are half the thickness of 1053 nm mirrors. As coatings decrease in thickness, the inclusion diameter that can be bounded into the film decreases. The laser resistance of nodular defects increases with decreasing inclusion diameter. Nodular defects are a fluence-limiting defect for 1053 nm multilayer mirrors while 351 nm mirrors are fluence limited by small interfacial defects. Little research has been on the damage mechanisms of visible mirror coatings for nanosecond length laser pulses. Depending on the dominant damage mechanism of 527 nm coatings, high fluence 527 nm transport mirrors may be realized.

4. CONCLUSIONS

Significant progress has been made within the optics industry to provide optics for large laser fusion programs. These include advances in glass melting technologies for amplifier slabs, KDP and DKDP crystal growth, deterministic finishing technologies, and high fluence multilayer optical coatings. Optical advances for a commercial fusion fission power plant will be in crystalline materials, laser glass compositions, mitigation technologies to prevent laser damage growth, and defect reduction within optical substrate and coating materials for increased laser resistance.

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DISCLAIMER

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